4.5 Nuclear and Particle Physics

This topic covers atomic structure, particle accelerators and the standard quark-lepton model.

This topic is the subject of current research, involving the acceleration and detection of high-energy particles. It may be taught by exploring a range of experiments such as

- alpha scattering and the nuclear model of the atom
- accelerating particles to high energy
- detecting and interpreting interactions between particles.

Candidates will be assessed on their ability to:

111 understand what is meant by *nucleon number (mass number)* and *proton number (atomic number)*

Nucleon number, A (mass number) = no. of neutrons + no. of protons

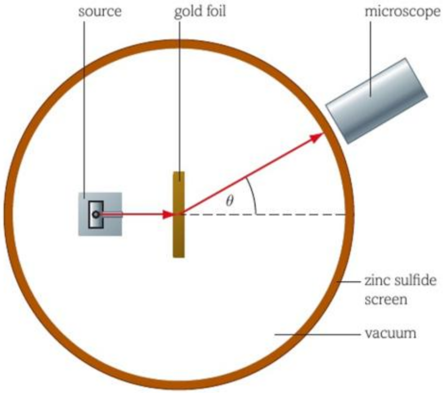
Proton number, Z (atomic number) = no. of protons
= no. of electrons in a neutral atom

Isotopes = atoms of the same element with the same number of protons but different number of neutrons

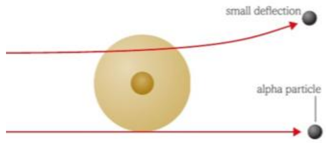
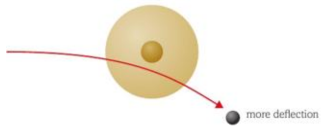
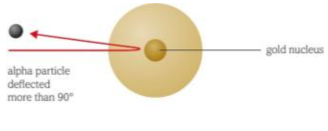
$$^{A}_{Z}X$$

112 understand how large-angle alpha particle scattering gives evidence for a nuclear model of the atom and how our understanding of atomic structure has changed over time

Alpha particle scattering observations and conclusions



Rutherford's apparatus included an alpha source and gold foil in an evacuated chamber which was covered in a fluorescent coating, which meant you could see where the alpha particles hit the inside of the chamber.
To observe the path of the alpha particles, there was a microscope which could be moved around the outside of the chamber

Angle of deflection/ degrees	Illustration	Evidence	Conclusion
0-10		Most alpha particles pass straight through with little deviation	Most of the atom is empty space
10-90		Some alpha particles deflected through a large angle	A large concentration of charge in one place
90-180		A few alpha particles are deflected back towards the source side of foil	Most of the mass of the atom and a large concentration of charge is in a tiny, central nucleus

113 understand that electrons are released in the process of thermionic emission and how they can be accelerated by electric and magnetic fields

$\mathrm{KE} = e\mathrm{V}$
where e is the charge of an electron and V is from the electric field

The force experienced by an electron moving in a magnetic field is always perpendicular to its motion

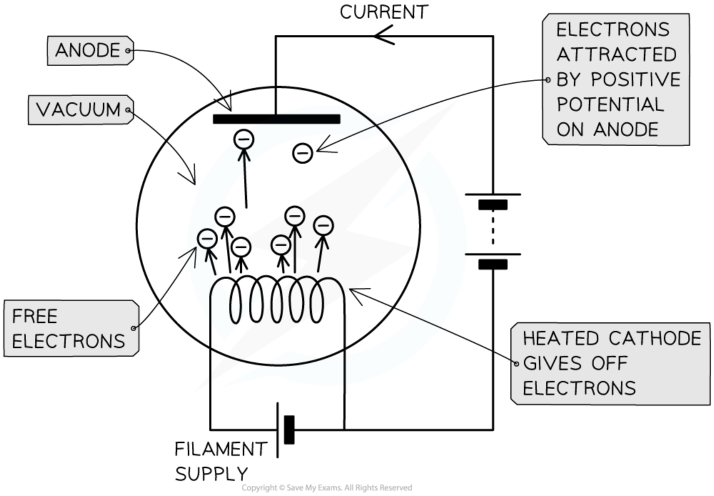
Thermionic emission is *the*
"the release of electrons from a metal surface caused by heating of the metal"

Recall the photoelectric effect- when electrons are released from the surface of a metal when incident with electromagnetic radiation as they absorb energy of the photons to escape- well, thermionic emission is the release of electrons just by the heating of the metal (i.e. by gaining thermal energy)

- When metals are **heated**, the conduction electrons within them gain **energy**
- If these electrons gain sufficient energy, they can leave the surface of the metal
- This means:
  KE gained by electron = Energy transferred across the potential difference

$$\frac{1}{2}mv^2 = QV$$

- Once electrons are released from a metal surface they can be accelerated by **electric** or accelerated radially by a **magnetic field** to increase their velocity



Copyright © Save My Exams. All Rights Reserved

- Electron guns use a potential difference to accelerate the electrons, which are released from the cathode by heating it (thermionic emission)
- The electrons are accelerated towards the anode (in positive direction), which has a small gap, the electrons which pass through this gap form a narrow electron beam which travels at a constant velocity beyond the anode

114 understand the role of electric and magnetic fields in particle accelerators (linac and cyclotron) and detectors (general principles of ionisation and deflection only)

Particle Accelerators

1. Linear Accelerators (LINAC)

A LINAC is formed by several cylindrical electrodes known as drift tubes which progressively increase in length along the accelerator (labelled A, B, C, D and E in the diagram below)

LINACs use **electric fields** within and between drift tubes which act as oppositely charged **electrodes**

- An **AC power supply** is connected across each tube to ensure ions are always **accelerated** from one to the next
  - The ions will be **attracted** to the **midpoint** of a tube
  - At this point, the AC supply will **switch** such that the ions are **repelled** to the exit, and attracted to the next tube
  - This process continues in a **straight line** all the way to the end of the accelerator
- The **frequency** of the AC supply is fixed
  - This means the polarity (positive or negative charge) of each tube switches at a **constant rate**

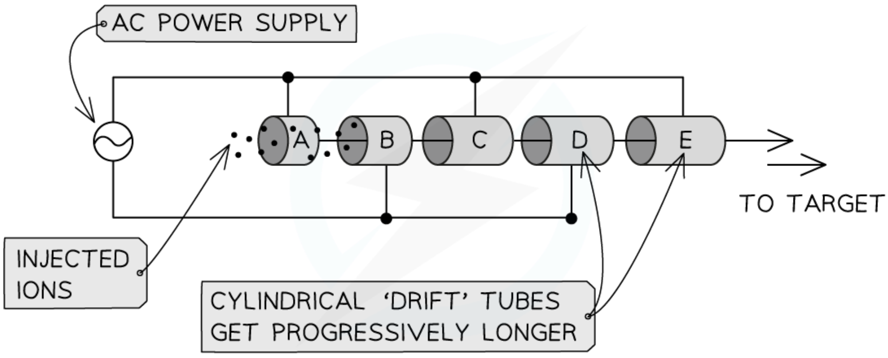
- Therefore, each tube must be built **successively longer**
  - This is because the ions are **speeding up**
  - Hence, this ensures ions spend the same amount of **time** under acceleration in each tube

Alternative Explanation

Adjacent electrodes (drift tubes) are connected to the opposite polarity of an alternating voltage (or AC power supply), which means that alternating electric fields are formed in the gaps between electrodes

This is so that when the electrons reach the midpoint of tube A, AC supply will switch so that tube A becomes negative and repels electrons out of A towards tube B which is now positive so electrons are attracted towards B and accelerates, and the process repeats in a straight line

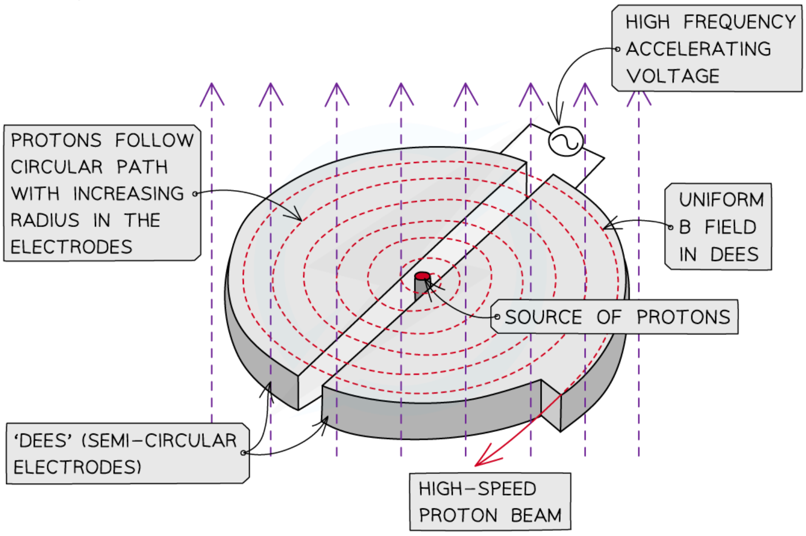
- If the particles accelerated are electrons, they are generated by an electrostatic machine such as a Van de Graff generator



2. Cyclotron

A cyclotron is formed of two **semi-circular electrodes** called “Dees”, with a **uniform magnetic field** acting perpendicular to the plane of the electrodes, and a **constant high frequency AC power supply** across each dee, which creates an **electric field** in the **gap** between them

- The charged particles move from the centre of one of the electrodes, and are deflected in a circular path by the magnetic field
- Because the magnetic **force exerted by the magnetic field is always perpendicular to the direction of travel**, the particle’s speed will not increase due to the magnetic field, which is why there is an alternating electric field between the dees
- Once the particles reach the edge of the dee, they begin to move across the gap between the dees, where they are **accelerated by the electric field** (i.e. the potential difference between the dees), meaning the radius of their circular path will increase as they move through the second dee and so on
- When the particles reach the gap again, the alternating electric field changes direction, allowing the particles to be accelerated in the same direction again



Particle Detectors

- When charged particles move through any medium, such as a gas, they transfer energy to it
- This is usually through the process of ionisation
  - High-energy ions transfer some of their energy to surrounding atoms, removing electrons
  - The ions and electrons produced are then accelerated by electric fields
  - Once these are discharged they form pulses of electric current
- Each pulse of electricity is counted by electronic counters connected by electrodes
  - 'Counts' are then interpreted as detection of individual particles

115

be able to derive and use the equation $r = \frac{}{BQ}$ for a charged particle in a magnetic field

The force exerted by a magnetic field on a charged particle is always perpendicular to its motion of travel, which causes charged particles to follow a circular path when in a magnetic field, because the force induced by the magnetic field acts as a centripetal force

By combining the formulas for centripetal force and magnetic force on a charged particle, you can derive the formula to find the radius of the particle's circular path:

$$F = BQv \qquad F = \frac{mv^2}{r}$$

$$BQv = \frac{mv^2}{r}$$

$$r = \frac{mv}{BQ}$$

You can simplify the equation above further by using the fact: p = mv

$$r = \frac{p}{BQ}$$

Where **p** is the particle's momentum, **Q** is its charge and **B** is the magnetic flux density.

116 be able to apply conservation of charge, energy and momentum to interactions between particles and interpret particle tracks

During interactions between particles,

"*Charge, Energy and Momentum must always be conserved*"

To interpret particle tracks,

Look at the particle tracks from a cloud or bubble chamber- both of these devices rely on the fact that charged particles are ionizing (they knock electrons out of atoms in its path), leaving behind a trail of ionised particles in their path which can be detected

A bubble chamber is a particle detection system in which the particles cause bubbles to be created in a superheated liquid, typically hydrogen

You can analyse bubble chamber tracks in the following ways:

- ➔ **Find the radius of curvature of tracks** - this will allow you to find out certain characteristics of the particle you are observing by using the following equation (which is derived above):

$$r = \frac{mv}{BQ}$$

- ➔ **Find the direction of curvature** - this will allow you to find out whether a particle has a positive or negative charge by using Fleming's left hand rule *(covered in topic 7.122)*.
- ➔ **Analyse interactions** - you see what particle interactions occur by looking at the shape of particle tracks:
  - ◆ If the tracks **stop suddenly** - particles have **collided**
  - ◆ If the tracks abruptly **change direction** - particles have **collided**
  - ◆ If the tracks look like they **have come from nothing** (as seen in the red and blue tracks highlighted below) - particles have been **created** from an **uncharged particle** (photon) which doesn't create tracks in a bubble chamber

117 understand why high energies are required to investigate the structure of nucleons

High Energy Particle Collisions to investigate the Structure of Nucleons

- When electrons are accelerated to very high energies, they can collide with nucleon targets (protons or neutrons)
- The scattering pattern is used to analyse the size and structure of nucleons
- To resolve detail, like the nucleon diameter, the de Broglie wavelength of the electron must be comparable (similar in size) to the size of the nucleon
- Since nucleons are very small (1.6 x 10^{-15}), very small wavelengths are used to investigate it and very small wavelengths mean very high energy particles

$$\lambda = \frac{h}{mv} \approx \text{nucleon diameter}$$

- Electrons are used as they do not experience the strong nuclear force unlike an alpha particle, which means they can get extremely close to the nucleons without interacting

Inside the Nucleon

- If electrons are accelerated to even higher energies, their de Broglie wavelength becomes even smaller as the **faster** the electrons, the **smaller** their de Broglie wavelength
- Hence, the electron wavelength becomes small enough to be used to resolve **internal** structure of the nucleon such as the individual quarks inside the nucleon

118

be able to use the equation $\Delta E = c^2 \Delta m$ in situations involving the creation and annihilation of matter and antimatter particles

Annihilation of Matter & Antimatter

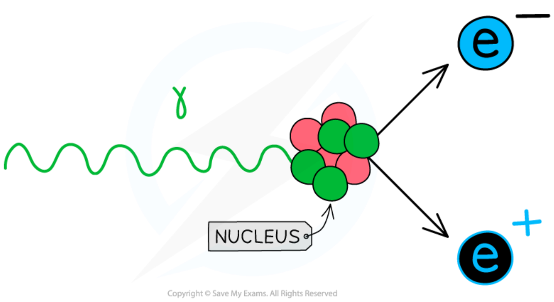
In the theory of special relativity Einstein proved that mass and energy are interchangeable and can be related by the following equation: $\Delta E = \Delta mc^2$

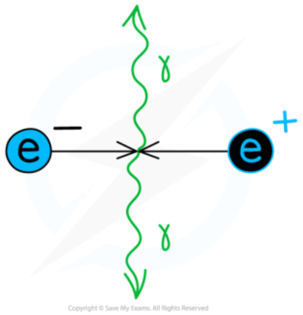
This means that at any time, mass and energy can be exchanged

Creation (pair production) is

when a photon interacts with a nucleus or atom and the energy of the photon is used to create a particle-antiparticle pair

This can only occur when the photon has energy greater than the total rest energy of both particles, any excess energy is converted into the kinetic energy of the particles





Annihilation is

where a particle and its corresponding antiparticle collide, as a result their masses are converted into energy- this energy, along with the kinetic energy of the two particles is released in the form of 2 photons moving in opposite directions to conserve momentum

Therefore, to create a particle & anti-particle pair, the energy carried by a single photon must be **at least** twice the rest-mass energy required, i.e.

$$2\Delta E = 2(c^2\Delta m)$$

This also means if a particle meets its anti-particle and annihilates, the energy carried away by **each** of the two photons E_{photon} is given by:

$$E_{photon} = hf = \frac{hc}{\lambda} = c^2\Delta m$$

(Kinetic Energy of photon = Total Energy – Rest mass energy of photon??)

119

be able to use MeV and GeV (energy) and MeV/c^2, GeV/c^2 (mass) and convert between these and SI units

Unit Conversions for Energy & Mass

1 eV is equal to the kinetic energy of an electron accelerated across a potential difference of 1 V or 1.6×10^{-19} J

1u is the atomic mass unit used in particle interactions = 1.66×10^{-27} kg (but it is not an SI unit) = 931.5 MeV/c^2

So, we can use E/c^2 instead, such as MeV/c^2 and GeV/c^2

120

understand situations in which the relativistic increase in particle lifetime is significant (use of relativistic equations not required)

Relativistic Situations

- When particles are travelling at speeds that are very close to the speed of light (relativistic speeds), relativistic effects begin to become important
- These are effects such as:
    - Time dilation
    - Length contraction

Time Dilation

- Time dilation causes time to run at different speeds depending on the motion of an observer
- Consequently, the lifetime of a particle moving at relativistic speeds recorded by a stationary observer would be longer than the actual time (as suggested by predictions)

> Muon decay provides experimental evidence for time dilation because muons enter the atmosphere at very high speeds and so experience significant time dilation, which affects how quickly they decay
>
> Muons are formed in the upper atmosphere and have a lifetime of around 2μs, which suggests that as they travel to the surface of the Earth, most would decay before reaching sea level
>
> However experimental evidence showed that most muons (around 80%) could be detected upon reaching sea level, even though more than 2μs had passed to an external observer, WHY?
>
> This can only be explained by **time dilation** as the muons are travelling at **close to the speed of light** and relativistic effect **increases particle lifetime** (for observer) so travels further than normally expected (before decaying)

Length Contraction

- Particles moving at very high velocities travel much further through detectors than expected

> If exotic particles produced in particle accelerators decayed within the particle chamber before escaping it, none would be detectable
>
> In fact, **many** types of exotic particles are detected
>
> This is evidence of length contraction

121

know that in the standard quark-lepton model particles can be classified as:

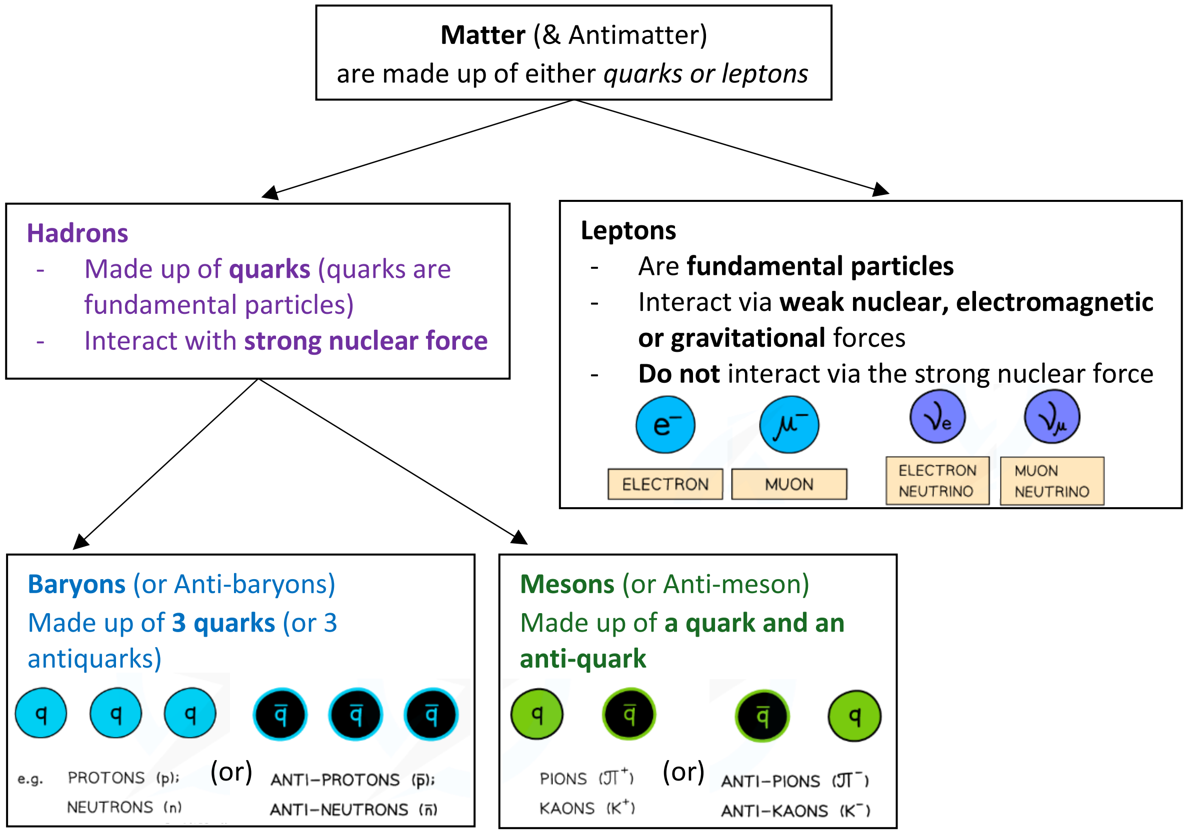
- baryons (e.g. neutrons and protons), which are made from three quarks
- mesons (e.g. pions), which are made from a quark and an antiquark
- leptons (e.g. electrons and neutrinos), which are fundamental particles
- photons

and that the symmetry of the model predicted the top quark

The Standard Model

- It is the theory of all the fundamental particles and how they interact
- This theory currently has the strongest experimental evidence

The **four fundamental forces** are:
Gravity
Electromagnetism
Strong nuclear forces
Weak nuclear forces



Matter (& Antimatter) are made up of either *quarks or leptons*

Hadrons

- Made up of **quarks** (quarks are fundamental particles)
- Interact with **strong nuclear force**

Leptons

- Are **fundamental particles**
- Interact via **weak nuclear, electromagnetic or gravitational** forces
- **Do not** interact via the strong nuclear force

Baryons (or Anti-baryons)
Made up of **3 quarks** (or 3 antiquarks)

Mesons (or Anti-meson)
Made up of **a quark and an anti-quark**

All particles can be classified as either ***Hadrons***, ***Leptons*** or ***photons***

Leptons are *fundamental particles*, meaning they cannot be broken down any further and they do not experience the strong nuclear force (one of the four fundamental forces)
Hadrons are formed of *quarks* and they experience the strong nuclear force
Photons are the *fundamental particles* which make up light. They are uncharged and have no mass. They mediate electromagnetic interaction (one of the four fundamental forces) They are also known as exchange bosons

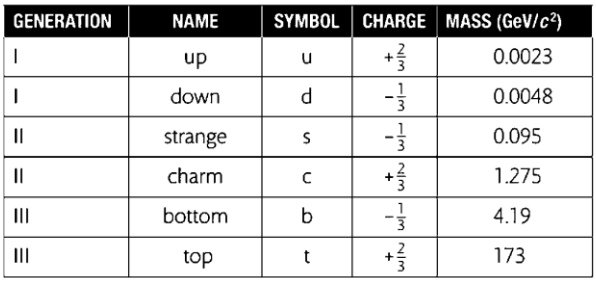
The standard model categorizes quarks and leptons by charge and mass

Increasing mass

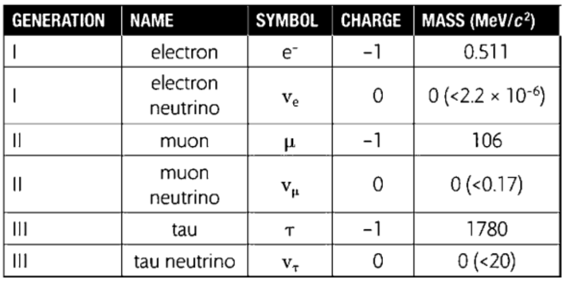
Generation	Quarks		Leptons	
I	u up $\left(+\frac{2}{3}e\right)$	d down $\left(-\frac{1}{3}e\right)$	e^- electron $(-1e)$	ν_e electron neutrino (0)
II	c charm $\left(+\frac{2}{3}e\right)$	s strange $\left(-\frac{1}{3}e\right)$	μ muon $(-1e)$	ν_μ muon neutrino (0)
III	t top $\left(+\frac{2}{3}e\right)$	b bottom $\left(-\frac{1}{3}e\right)$	τ tau $(-1e)$	ν_τ tau neutrino (0)

In the standard model,

Quarks	Leptons



GENERATION	NAME	SYMBOL	CHARGE	MASS (GeV/c^2)
I	up	u	$+\frac{2}{3}$	0.0023
I	down	d	$-\frac{1}{3}$	0.0048
II	strange	s	$-\frac{1}{3}$	0.095
II	charm	c	$+\frac{2}{3}$	1.275
III	bottom	b	$-\frac{1}{3}$	4.19
III	top	t	$+\frac{2}{3}$	173



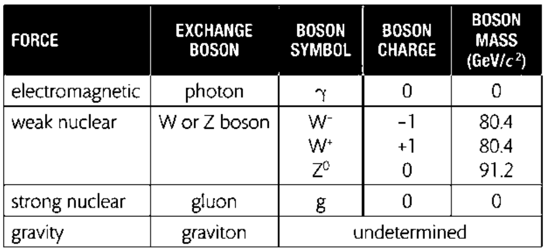
GENERATION	NAME	SYMBOL	CHARGE	MASS (MeV/c^2)
I	electron	e^-	−1	0.511
I	electron neutrino	ν_e	0	0 (<2.2 × 10^{-6})
II	muon	μ	−1	106
II	muon neutrino	ν_μ	0	0 (<0.17)
III	tau	τ	−1	1780
III	tau neutrino	ν_τ	0	0 (<20)

Extra Information!

You *do not need to know* all the exchange bosons, only the photons

Exchange bosons are particles that enable the transfer of force

Each of the four fundamental particles has its own exchange boson



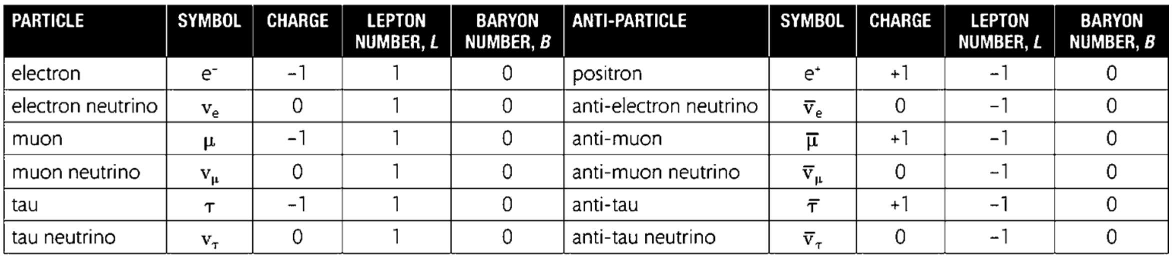
FORCE	EXCHANGE BOSON	BOSON SYMBOL	BOSON CHARGE	BOSON MASS (GeV/c^2)
electromagnetic	photon	γ	0	0
weak nuclear	W or Z boson	W^- W^+ Z^0	−1 +1 0	80.4 80.4 91.2
strong nuclear	gluon	g	0	0
gravity	graviton	undetermined		

122 know that every particle has a corresponding antiparticle and be able to use the properties of a particle to deduce the properties of its antiparticle and vice versa

Rest mass-energy is the energy equivalent to the mass of the particle at rest

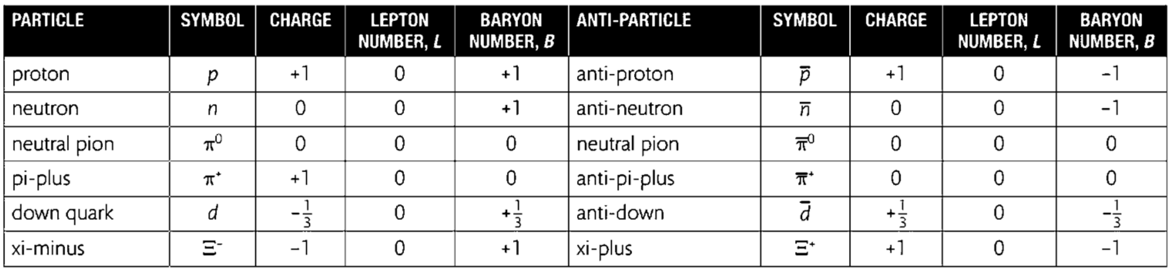
Antimatter

- For every type of particle, there is a corresponding antiparticle which has the **same *mass* and *rest mass-energy*** but with **opposite charges**
- A neutral particle, such as a neutron or neutrino or photon, is its own antiparticle
- Mass of particle-antiparticle pair is identical but they have opposite electric charge



PARTICLE	SYMBOL	CHARGE	LEPTON NUMBER, *L*	BARYON NUMBER, *B*	ANTI-PARTICLE	SYMBOL	CHARGE	LEPTON NUMBER, *L*	BARYON NUMBER, *B*
electron	e^-	−1	1	0	positron	e^+	+1	−1	0
electron neutrino	ν_e	0	1	0	anti-electron neutrino	$\bar{\nu}_e$	0	−1	0
muon	μ	−1	1	0	anti-muon	$\bar{\mu}$	+1	−1	0
muon neutrino	ν_μ	0	1	0	anti-muon neutrino	$\bar{\nu}_\mu$	0	−1	0
tau	τ	−1	1	0	anti-tau	$\bar{\tau}$	+1	−1	0
tau neutrino	ν_τ	0	1	0	anti-tau neutrino	$\bar{\nu}_\tau$	0	−1	0

table A Leptons and anti-leptons and their properties.



PARTICLE	SYMBOL	CHARGE	LEPTON NUMBER, *L*	BARYON NUMBER, *B*	ANTI-PARTICLE	SYMBOL	CHARGE	LEPTON NUMBER, *L*	BARYON NUMBER, *B*
proton	p	+1	0	+1	anti-proton	$\bar{p}$	+1	0	−1
neutron	n	0	0	+1	anti-neutron	$\bar{n}$	0	0	−1
neutral pion	π^0	0	0	0	neutral pion	$\bar{\pi}^0$	0	0	0
pi-plus	π^+	+1	0	0	anti-pi-plus	$\bar{\pi}^+$	0	0	0
down quark	d	$-\frac{1}{3}$	0	$+\frac{1}{3}$	anti-down	$\bar{d}$	$+\frac{1}{3}$	0	$-\frac{1}{3}$
xi-minus	Ξ^-	−1	0	+1	xi-plus	Ξ^+	+1	0	−1

123 understand how to use laws of conservation of charge, baryon number and lepton number to determine whether a particle interaction is possible

Laws of conservation of charge, baryon number and lepton number

A particle interaction is only possible if all conversation laws are obeyed

Along with the conversation of energy and momentum, the following properties must be conserved in a particle interaction:

- **Charge**

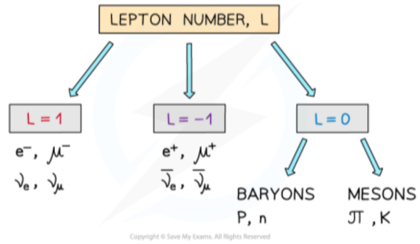
Protons have a charge ***Q* = +1**
Electrons have a charge ***Q* = −1**
Up quarks have a charge ***Q* = +2/3**
Neutral particles, like photons and neutrinos, have a charge ***Q* = 0**

- **Baryon number** - this shows whether a particle is a baryon (1), antibaryon (-1) or neither (0)

Baryons have a baryon number ***B* = +1**
Anti-baryons have a baryon number ***B* = −1**
Particles that are not baryons have a baryon number ***B* = 0**

The up (u), down (d) and strange (s) quark have a baryon number of 1/3 each
The anti–up, anti–down and anti–strange quarks have a baryon number of −1/3 each

- **Lepton number** - this shows whether it is a lepton (1), antilepton (-1) or neither (0)



!These are called quantum numbers and they must always be conserved

124 be able to write and interpret particle equations given the relevant particle symbols.

Particle Interaction Equations

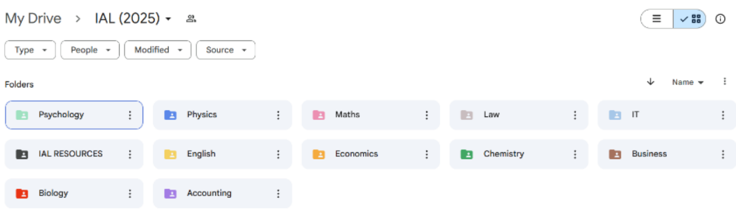
Particle	Alpha (α)	Beta minus (β^-)	Beta plus (β^+)	Gamma (γ)
Composition	2 protons + 2 neutrons	Electron (e^-)	Positron (e^+)	Electromagnetic wave
Charge	+2e	−1e	+1e	0
Mass	4u	0.0005u	0.0005u	0
Speed	0.05c	Less than 0.99c	Less than 0.99c	1c

To know whether a particle interaction can occur, check whether each quantum number (Charge, Baryon, Lepton number) is equal on both sides of the equation

- If even one of them, apart from strangeness in weak interactions, is not conserved then the interaction cannot occur

Remarks

- Disclaimer: This Self-Study Booklet series are not intended as a textbook replacement but instead are meant to be used alongside it
- This booklet is primarily exam-based and has been produced to remove unnecessary information from the book to make it into a simpler and more compact form factor
- Thank you all for using this Self-Study Booklet and if you would like to find more resources like this one, do check out this google drive: https://drive.google.com/drive/folders/1qpY-sGR9iinJbnquB53hx8pLk49pyxd1?usp=drive_link
- You will be redirected here:



(Note that there are only Self-Study Booklets/ CAQs for Physics and Chemistry)

- Do keep in mind that this is still a work-in-progress and you are welcome to add more resources to it- just drop a text to @aeth_en on discord!

Importance notice regarding Usage Rights

- There are certain images and illustrations used in this document from many different sources The ownership of these images and/or illustrations belong to their rightful owners
- I do not own these images and/or illustrations
- Reprinting or Copying of this document and selling/ profiting from it is strictly prohibited
- This Self-Study Booklet is intended for students worldwide studying for the Edexcel International A-Levels and will remain free of charge

Help us improve

- This booklet is in its first edition so may contain mistakes here and there
- Please let us know of any room for improvement so that we can make it better!
- Contact: mth.2021education@gmail.com or @aeth_en on discord
- Best of luck in your A-Levels journey!!